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## Radial symmetry of self-similar solutions for semilinear heat equations

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We consider the symmetry properties of positive solutions of the equation

$$\Delta u + \frac{1}{2}x \cdot \nabla u + \frac{1}{p-1}u + u^p = 0 \quad \text{in } \mathbf{R}^n, \quad (1.1)$$

where  $n \geq 2$  and  $p > 1$ . This equation arises in the study of (forward) self-similar solutions of the semilinear heat equation

$$w_t = \Delta w + w^p \quad \text{in } \mathbf{R}^n \times (0, \infty). \quad (1.2)$$

It is well known that if  $w(x, t)$  satisfies (1.2), then, for  $\mu > 0$  the rescaled functions

$$w_\mu(x, t) = \mu^{2/(p-1)}w(\mu x, \mu^2 t)$$

define a one parameter family of solutions to (1.2). A solution  $w$  is said to be self-similar, when  $w_\mu(x, t) = w(x, t)$  for all  $\mu > 0$ . It can be easily checked that  $w$  is a self-similar solution to (1.2) if and only if  $w$  has the form

$$w(x, t) = t^{-1/(p-1)}u(x/\sqrt{t}), \quad (1.3)$$

where  $u$  satisfies the elliptic Eq. (1.1). Moreover, if  $u$  has spherical symmetry, that is if  $u = u(r)$ ,  $r = |x|$ , then  $u$  satisfies the ordinary differential equation

$$u'' + \left(\frac{n-1}{r} + \frac{r}{2}\right)u' + \frac{1}{p-1}u + u^p = 0, \quad r > 0. \quad (1.4)$$

Such self-similar solutions are often used to describe the large time behavior of global solutions to the Cauchy problem, see, e.g., [11, 13, 3, 14, 5, and 15], and to show nonuniqueness of solution to (1.2) with zero initial data in a certain functional space, see [12].

First we state the result concerning the symmetry properties of the solution of (1.1).

**THEOREM 1.1.** *Let  $u \in C^2(\mathbf{R}^n)$  be a positive solution of (1.1) such that*

$$u(x) = o(|x|^{-2/(p-1)}) \quad \text{as } |x| \rightarrow \infty. \quad (1.5)$$

*Then  $u$  must be radially symmetric about the origin.*

The proof of Theorem 1.1 is based on the moving planes argument. This technique was developed by Serrin [18] in PDE theory, and extended and generalized by Gidas, Ni, and Nirenberg [9, 10]. We remark that with a change of variables we are still able to prove a radial symmetry result for Eq. (1.1).

Let us consider the problem

$$\begin{cases} u'' + \left( \frac{n-1}{r} + \frac{r}{2} \right) u' + \frac{1}{p-1} u + |u|^{p-1} u = 0, & r > 0, \\ u'(0) = 0 \quad \text{and} \quad u(0) = \alpha \in \mathbf{R}. \end{cases} \quad (1.6)$$

The problem (1.6) has been investigated extensively in [12, 16, 20, and 2]. We denote by  $u(r; \alpha)$  the unique solution of (1.6). We recall that  $u(r; \alpha)$  has the following properties:

- (i)  $\lim_{r \rightarrow \infty} r^{2/(p-1)} u(r; \alpha) = L(\alpha)$  exists and is finite for every  $\alpha \in \mathbf{R}$  (see [12, Theorem 5]);
- (ii) if  $L(\alpha) = 0$ , then there exists a constant  $A \neq 0$  such that

$$u(r; \alpha) = A e^{-r^2/4} r^{2/(p-1)-n} \{1 + O(r^{-2})\} \quad \text{as } r \rightarrow \infty$$

(see [16, Theorem 1]);

- (iii) if  $p \geq (n+2)/(n-2)$ , then  $u(r; \alpha)$  is positive on  $[0, \infty)$  and  $L(\alpha) > 0$  for every  $\alpha > 0$  (see [12, Theorem 5]);

- (iv) if  $(n+2)/n < p < (n+2)/(n-2)$ , then there exists a unique  $\alpha > 0$  such that  $u(r; \alpha)$  is positive on  $[0, \infty)$  and  $L(\alpha) = 0$  (see [20, Theorem 1] and [2, Theorem 1.2 and Corollary 1.3]).

By virtue of Theorem 1.1 we obtain the following:

**COROLLARY 1.1.** (i) *Assume that  $p \geq (n+2)/(n-2)$ . Then there exists no positive solution  $u$  of (1.1) satisfying (1.5).*

(ii) *Assume that  $(n+2)/n < p < (n+2)/(n-2)$ . Then there exists a unique positive solution  $u(x)$  satisfying (1.5). Moreover, the solution  $u$  is radially symmetric about the origin.*

*Remark.* The result (i) is differently proven by [3, Proposition 4.3] based on the Pohozaev identity.

Following the notations in [3] and [14], we define

$$L^2(K) = \{u : \mathbf{R}^n \rightarrow \mathbf{R}; \int_{\mathbf{R}^n} |u|^2 K(x) dx < \infty\} \quad \text{and}$$

$$H^1(K) = \{u : \mathbf{R}^n \rightarrow \mathbf{R}; \int_{\mathbf{R}^n} (|u|^2 + |\nabla u|^2) K(x) dx < \infty\},$$

where  $K(x) = \exp(-|x|^2/4)$ . Escobedo and Kavian have shown in [3, Proposition 3.5] that if  $1 < p < (n+2)/(n-2)$  and if  $u \in H^1(K)$  is a solution of (1.1), then  $u \in C^2(\mathbf{R}^n)$  and satisfies  $u(x) = O(\exp(-|x|^2/8))$  as  $|x| \rightarrow \infty$ . As a consequence of Corollary 1.1, we obtain the following:

**COROLLARY 1.2.** *Assume that  $(n+2)/n < p < (n+2)/(n-2)$ . Then the problem*

$$\begin{cases} \Delta u + \frac{1}{2}x \cdot \nabla u + \frac{1}{p-1}u + u^p = 0 & \text{in } \mathbf{R}^n, \\ u \in H^1(K) \quad \text{and} \quad u > 0 & \text{in } \mathbf{R}^n, \end{cases} \quad (1.7)$$

*has a unique solution.*

Let us consider the Cauchy problem

$$\begin{cases} w_t = \Delta w + w^p & \text{in } \mathbf{R}^n \times (0, \infty), \\ w(x, 0) = \tau w_0 & \text{in } \mathbf{R}^n, \end{cases} \quad (1.8)$$

where  $w_0 \in L^2(K) \cap L^\infty(\mathbf{R}^n)$ ,  $w_0 \geq 0$ , and  $\tau > 0$  is a parameter. We denote by  $w(x, t; \tau)$  the unique solutions of (1.8) (see [15]). Combining the result by Kawanago [15, Theorem 1] and Corollary 1.2, we obtain the following, where the asymptotic behavior of  $w(\cdot, t; \tau)$  as  $t \rightarrow \infty$  becomes clearer.

**COROLLARY 1.3.** *Assume that  $(n+2)/n < p < (n+2)/(n-2)$ . Then there exists a unique  $\tau_0 > 0$  such that the solution  $w(x, t; \tau)$  is a global solution if  $\tau \in (0, \tau_0]$ , and  $w(x, t; \tau)$  blows up in finite time if  $\tau \in (\tau_0, \infty)$ . Moreover,  $w(x, t; \tau_0)$  satisfies*

$$\lim_{t \rightarrow \infty} \left\| t^{1/(p-1)} w(\cdot, t; \tau_0) - u_0(\cdot/\sqrt{t}) \right\|_{L^\infty(\mathbf{R}^n)} = 0,$$

*where  $u_0$  is a unique solution of the problem (1.7).*

Next we consider the existence of nonradial solutions of (1.1). Let  $p > (n+2)/n$  and let  $U(r)$  be a positive solution of (1.4) satisfying

$$U'(0) = 0 \quad \text{and} \quad \lim_{r \rightarrow \infty} r^{2/(p-1)} U(r) > 0. \quad (1.9)$$

The existence of such  $U$  is obtained by [12, Theorem 5]. Define  $\ell = \ell(U) > 0$  as

$$\ell = \lim_{r \rightarrow \infty} r^{2/(p-1)} U(r). \quad (1.10)$$

We investigate the Cauchy problem for Eq. (1.2) with

$$w(x, 0) = w_0 \in L^1_{\text{loc}}(\mathbf{R}^n), \quad (1.11)$$

where

$$0 \leq w_0(x) \leq \ell |x|^{-2/(p-1)}, \quad w_0 \not\equiv 0, \quad x \in \mathbf{R}^n \setminus \{0\}. \quad (1.12)$$

Relation (1.11) is taken in the sense of  $L^1_{\text{loc}}(\mathbf{R}^n)$ , that is,

$$\int_K |w(x, t) - w_0(x)| dx \rightarrow 0 \quad \text{as } t \rightarrow 0$$

for any compact subset  $K$  of  $\mathbf{R}^n$ . We note that  $w_0 \in L^1_{\text{loc}}(\mathbf{R}^n)$  if (1.12) holds with  $p > (n+2)/n$ .

**THEOREM 1.2.** *Let  $p > (n+2)/n$ . Assume that (1.12) holds, where  $\ell$  is the constant in (1.10). Then there exists a positive solution  $w \in C^{2,1}(\mathbf{R}^n \times (0, \infty))$  of (1.2) and (1.11). Assume, furthermore, that  $w_0 \in C(\mathbf{R}^n \setminus \{0\})$ , then  $w$  satisfies*

$$w(x, t) \rightarrow w_0(x) \quad \text{as } t \rightarrow 0 \quad \text{uniformly in } |x| \geq r \text{ for every } r > 0. \quad (1.13)$$

Moreover,  $w$  is self-similar if  $\mu^{2/(p-1)} w_0(\mu x) = w_0(x)$  for every  $\mu > 0$ .

**COROLLARY 1.4.** *Let  $p > (n+2)/n$ . Assume that  $A : S^{n-1} \rightarrow \mathbf{R}$  is continuous and satisfies*

$$0 \leq A(\sigma) \leq \ell, \quad A \not\equiv 0, \quad \sigma \in S^{n-1}. \quad (1.14)$$

*Then there exists a positive self-similar solution  $w \in C^{2,1}(\mathbf{R}^n \times (0, \infty))$  of (1.2) satisfying (1.11) and (1.13) with  $w_0(x) = A(x/|x|)|x|^{-2/(p-1)}$ .*

Recall that self-similar solutions  $w$  to (1.2) have the form (1.3) with  $u$  satisfying (1.1). Therefore,  $w(\sigma, t) = r^{2/(p-1)} u(r\sigma)$  for  $\sigma \in S^{n-1}$ , where  $r = 1/\sqrt{t}$ . Then we obtain the following corollary, which shows that condition (1.5) in Theorem 1.1 is crucial.

COROLLARY 1.5. Let  $p > (n + 2)/n$ . Assume that  $A : S^{n-1} \rightarrow \mathbf{R}$  is continuous and satisfies (1.14). Then there exists a positive non-radial solution  $u$  of (1.1) satisfying

$$r^{2/(p-1)}u(r\sigma) \rightarrow A(\sigma) \quad \text{as } r \rightarrow \infty \quad \text{uniformly in } \sigma \in S^{n-1}.$$

Remark. (i) If  $1 < p \leq (n + 2)/n$ , no time global, non-negative, and nontrivial solution exists in (1.2) (see, e.g., [7], [19]). Therefore, (1.1) admits a positive solution only if  $p > (n + 2)/n$ .

(ii) We find that the solution  $w$  of (1.2) and (1.11) obtained in Theorem 1.2 is a minimal solution of the integral equation

$$w(x, t) = \int_{R^n} \Gamma(x - y : t) w_0(y) dy + \int_0^t \int_{R^n} \Gamma(x - y : t - s) [w(y, s)]^p dy ds,$$

where  $\Gamma(x : t) = (4\pi t)^{-n/2} e^{-|x|^2/4t}$ . See the proof of Theorem 1.2 below.

(iii) Galaktionov and Vazquez [8] studied the Cauchy problem (1.2) and (1.11) with singular initial values for the case  $p > n/(n - 2)$ .

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